Combined Radiometer–Radar Microphysical Profile Estimations with Emphasis on High-Frequency Brightness Temperature Observations

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ABSTRACT

Information about the vertical microphysical cloud structure is useful in many modeling and predictive practices. Radiometers and radars are used to observe hydrometeor properties. This paper describes an iterative retrieval algorithm that combines the use of airborne active and wideband (10–340 GHz) passive observations to estimate the vertical content and particle size distributions of liquid and frozen hydrometeors. Airborne radar and radiometer observations from the third Convection and Moisture Experiment (CAMEX-3) were used in the retrieval algorithm as constraints. Nadir profiles were estimated for 1 min each of flight time (approximately 12.5 km along track) for anvil, convective, and quasi-stratiform clouds associated with Hurricane Bonnie (August 1998). The physically based retrieval algorithm relies on high frequencies ($\geq$150 GHz) to provide details on the frozen hydrometeors. Neglecting the high frequencies yielded acceptable estimates of the liquid profiles, but the ice profiles were poorly retrieved. The wideband observations were found to more than double the estimated frozen hydrometeor content as compared with retrievals using only 90 GHz and below. The convective and quasi-stratiform iterative retrievals quickly reached convergence. The complex structure of the frozen hydrometeors required the most iterations for convergence for the anvil cloud type. Nonunique profiles, within physical and theoretical bounds, were retrieved for thin anvil ice clouds. A qualitative validation using coincident in situ CAMEX-3 observations shows that the retrieved particle size distributions are well corroborated with independent measurements.

1. Introduction

Knowledge of the vertical microphysical cloud structure is important in many aspects of meteorology, such as for determining precipitation rates and latent heating profiles, and for forecasting hurricane intensity (Simpson et al. 1996). In addition, hydrometeor profiles are used to improve global change and cloud-resolving models. Severe storms or intense rain can also affect earth–satellite communication transmissions. For these reasons, accurate estimates of the vertical profile of liquid and frozen hydrometeor particle size distributions are vital to atmospheric research, meteorological, and communications communities. In an effort to estimate precipitation profile information, despite sparsely situated ground-based sensors, airborne- and satellite-based remote sensing instruments have been employed (Kummerow et al. 2000).

The challenge of using airborne or satellite remote

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sensors is determining the appropriate instruments for the parameter of interest. Infrared instruments provide temperature and relative humidity profiles in cloud-free regions. Lidars can be used to remotely sense cirrus clouds, water clouds, and aerosols (e.g., Wang and Sassen 2002; Savov et al. 2002). However, infrared and lidar instruments cannot be used to reliably obtain detailed precipitating hydrometeor information. A single-channel active microwave radar can only provide one of the two–six key parameters needed to fully characterize the particle size distribution (PSD) at each range gate. A passive multifrequency microwave radiometer allows probing into the different hydrometeor layers of the clouds, and the different channels are sensitive to various hydrometeor types (e.g., liquid vs frozen). The high frequencies (≥ 89 GHz) of the radiometer are more sensitive to frozen hydrometeors, while the low frequencies are mostly sensitive to liquid hydrometeors. However, radiometers are limited to sensing vertically integrated information about the hydrometeor structure. In addition, the relationships between hydrometeor characteristics and the upwelling brightness temperatures are both nonlinear and nonunique.

By combining active radar and passive radiometers, the opportunities to estimate hydrometeor profiles and cloud characteristics improve (Marzano et al. 1999). In fact, the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000) was the first satellite to include both a radar and radiometer designed to measure rainfall. Several radar–radiometer retrieval algorithms have been developed for use with the TRMM satellite (e.g., Olson et al. 1996; Sauvageot 1996; Viltard et al. 2000). Prior to TRMM, most existing remote sensing methodologies for estimating cloud structure independently relied on either radiometer or radar observations (e.g., Meneghini et al. 1997).

Associated with TRMM are calibration/validation field campaigns. One such field campaign was the third Convection and Moisture Experiment (CAMEX-3), which was based in southern Florida during August and September of 1998 (Geerts et al. 2000). The Texas and Florida Underflights (TEFLUN-B) field campaign combined resources with CAMEX-3 with the purpose of underflying the TRMM satellite. Multiple instruments located on the ground, low- and high-altitude aircraft, and satellites were used to observe convective and hurricane systems. Of particular interest for this work are measurements from instruments on the high-altitude Earth Resources-2 (ER-2) aircraft that provided a single active channel at 9.6 GHz and 11 brightness temperature channels ranging from 10.7 to 340 GHz during Hurricane Bonnie on 26 August 1998. The higher-frequency channels are extremely useful for determining and constraining the PSDs of the frozen hydrometeors (Deeter and Evans 2000) and to provide a unique aspect to this work in relation to other combined radar–radiometer retrieval algorithms (e.g., Marzano et al. 1999).

5. Summary

This paper has provided retrieval estimates of precipitation profiles and frozen hydrometeor profiles when using wideband radiometer observations plus radar observations. Profiles of hydrometeor characteristics were estimated using an iterative retrieval algorithm. The algorithm minimized the differences between forward calculations and observed radar and radiometer observations from the ER-2 aircraft obtained during CAMEX-3. The advantages of this retrieval algorithm are 1) the use of high-frequency channels to provide details of the frozen hydrometeors, and 2) combining radar and radiometer observations.

Contents and particle size distributions for spherical rain, cloud water, and frozen hydrometeors were estimated for profiles extending to 18 km with vertical spacing of 0.5 km. The retrieval was performed on anvil, convective, and quasi-stratiform cloud types. Surface winds speeds were varied for the three regions depending on their distance from Hurricane Bonnie's eye. The anvil cloud type required the most iterations in order to resolve the unknowns related to the characteristics of the frozen hydrometeors. The quasi-stratiform region met the convergence criterion the quickest because the initialization procedure used drop sizes more applicable to stratiform cloud types.

The retrieval results were qualitatively compared using observations from the NAST-M on the ER-2 and the CAPAC 2D-C probe on the DC-8 aircraft. The brightness temperatures of the outermost wings of the 50–60- and 118-GHz oxygen bands, as measured by the NAST-M, were within the convergence criteria (less than 10 K from the calculated brightness temperature values). Likewise, observations from the PMS 2D-C probe on the DC-8 aircraft flying at 12 km above the earth's surface were used to validate the particle size distributions of the anvil region retrievals. The retrieved anvil particle sizes and number densities matched the measured 2DC probe microphysics well. Unfortunately, the DC-8 was above the cloud tops for the convective and quasi-stratiform regions and no validation using the PMS 2D-C data could be performed for them.

The retrieved profiles contain considerable information about the cloud structure and hydrometeor size distribution profiles. More importantly, this work shows that high-frequency microwave channels (≥ 150 GHz) provide information needed in order to define the frozen hydrometeor characteristics found at the upper-altitude levels of a cloud. Even though the retrieved anvil profiles may not have unique frozen hydrometeor characteristics, the range of solutions is relatively insignificant with respect to estimates of precipitation rate, hurricane intensity, and latent heating profiles. With additional analysis this research can be used to improve cloud-resolving and global change models. Furthermore, this work shows that high-frequency microwave channels (≥ 150 GHz) provide information needed in order to define the frozen hydrometeor characteristics found at the upper-altitude levels of a cloud.